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an effect of gravitational amplification bias ?**

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Accepted for Publication in:

**Monthly Notices  
of the Royal Astronomical Society**

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# A search for the associations of distant radio-bright quasars with Abell clusters: an effect of gravitational amplification bias ?

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## ABSTRACT

The theory predicts that the effect of gravitational lensing by the matter associated with clusters of galaxies can magnify background sources, leading to an enhancement of source number density around foreground clusters of galaxies. We conduct a search for the associations of distant radio-bright quasars with Abell clusters using the 1-Jy and 2-Jy all-sky catalogs. Statistics turns to be very poor on the basis of the 1-Jy sample, which shows no correlations between the distant radio quasars with the foreground Abell clusters above  $1\sigma$  level. However, an apparent association ( $> 1\sigma$ ) of the 2-Jy radio sources with the foreground Abell clusters has been detected on scale of  $\sim 20$  arcminutes. We point out that this enhancement is unlikely to be produced by the statistical gravitational lensing hypothesis utilizing the matter associated with a population of isolated clusters unless (1)their velocity dispersion is a few times larger than the presently adopted value and/or (2)the intrinsic counts of the radio-bright sources with flux have a steeper slope than the presently observed ones. This indicates that (1)the observed associations, if real, can be the integrated result of all the matter along the line of sight to the distant quasars, namely, the weak lensing effect of clusters of galaxies that trace large-scale structures of the universe, and/or (2)the number counts of the radio-bright sources have been seriously contaminated by lensing.

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**Key Words:** gravitational lensing – quasars: general – radio sources: general – galaxies: clustering

# 1. Introduction

One of the important consequences of statistical gravitational lensing, as first realized by Gott & Gunn (1974) before the discovery of the first lensed quasar pair, is that high-redshift quasars may associate with low-redshift galaxies because flux-limited samples can pick up the intrinsically fainter quasars magnified by the effect of gravitational lensing of foreground galaxies, i.e., amplification bias. Since the early statistical report of the observational evidence on the presence of associations of the optically selected quasars with galaxies (Tyson, 1986; Webster et al., 1988), the subsequent work has been devoted to the confirmations of such associations (see Wu (1994) for a summary) including in different wavelengths. Among these, Fugmann (1988; 1990) found an association of relatively bright galaxies with distant radio quasars, and Bartelmann & Schneider (1993c) claimed a correlation between quasars and IRAS galaxies. No matter whether these associations relate to foreground galaxies alone or to even large-scale structures (Bartelmann & Schneider, 1993a,b,c), the effect of gravitational lensing has been found to be the natural explanations so far.

Recently, Wu & Hammer (1994) have theoretically investigated if distant objects can be associated with foreground galaxy clusters through the mechanism of gravitational amplification bias. They have concluded that it is possible nowadays to observe these associations similar to the quasar-galaxy ones. Indeed, several observations have indicated that foreground clusters of galaxies can act as strong or weak lenses for distant objects, such as galaxies and quasars. Giant luminous arcs provide a strong evidence on the very efficient lenses of clusters of galaxies for background galaxies (Lynds & Petrosian, 1986; Soucail et al., 1987; Wu & Hammer, 1993), while two quasars have been found to be due to the weak gravitational lensing by the matter associated with clusters of galaxies (Stickel & Kühr, 1992; Bonnet et al., 1993). In fact, a few years ago some of the high-redshift galaxies in the 3CR were already shown to be magnified by foreground clusters of galaxies (Hammer & Le Fèvre, 1990, references therein). During the preparation of this paper we learnt that a statistical significant overdensity of high redshift quasars in the directions of foreground galaxy clusters has been also detected (Rodrigues-Williams & Hogan 1993).

On the other hands, in order to reach a statistically significant enhancement by gravitational lensing, source counts should exhibit a very steep slope with flux. Radio-bright sources then provide the ideal sample to such a purpose. The least-squares fit to a power-law using the data of the  $S_{2.7\text{GHz}} \geq 0.1$  Jy sample, the  $S_{2.7\text{GHz}} \geq 1.5$  Jy sample and the  $S_{2.7\text{GHz}} \geq 2$  Jy sample (Dunlop & Peacock, 1990) gives the surface number density of radio sources  $N(> S) \sim S^{-1.62}$ . The enhancement factor induced by amplification bias, independent of the specific lensing models, can be evaluated through  $q = [N(> S/A)/N(> S)](1/A)$  (Narayan, 1989), where  $A$  is the magnification. Fig.1 shows the variation of  $q$  with  $A$  for radio-bright sources of  $S_{2.7\text{GHz}} \geq 1$  Jy. The full variations of  $q$  with  $S$  and  $A$  can be found in Wu & Hammer (1994). It turns out that a large enhancement of radio-bright sources around the foreground lensing objects can be expected at moderate magnification.

The purpose of this paper is to search for the possible associations of foreground clusters of galaxies with distant radio-bright quasars. A galaxy cluster alone can act as a strong lens, as was shown above. Moreover, if clusters of galaxies trace the large-scale structure of the universe, distant quasars may be further affected by the weak lensing effect of large-scale inhomogeneities (Bartelmann & Schneider, 1993a,b,c), enhancing the chance of observing the associations. The samples of distant radio-bright quasars are extracted from the flux-limited radio source surveys of Kühr et al. (1981) and of Wall & Peacock (1985), and Abell clusters of galaxies are chosen for the lensing objects. As a comparison, we have noticed that Rodrigues-Williams & Hogan (1993) used the Large Bright Quasar Survey as the source sample and the small Zwicky clusters as the lensing objects.

## 2. Sample selections

The all-sky catalog of 4073 Abell rich clusters of galaxies (Abell, Corwin & Olowin, 1989) constitutes the well-defined sample at relatively lower redshifts, nearly completed to  $z < 0.2$ . With the available redshift measurements for 121 clusters (Struble & Rood, 1991), the most have  $z < 0.2$  and the maximum reaches 0.4. Therefore, Abell clusters can be regarded as foreground lensing objects for the well separated distant sources.

We firstly choose the radio-bright sources from the Kühr et al. (1981) 1-Jy catalog selected at 5 GHz, covering the whole sky of  $|b^II| > 10^\circ$ . We have added the newly measured redshifts from the recent observations (Stickel, kühr & Fried, 1989, 1993; Stickel & kühr, 1993a,b,c; Hewitt & Burbidge, 1993). The update catalog contains 518 sources and 90% of them have spectroscopically determined redshifts. To ensure that the sources are distant enough to act as the lensed targets and are not cluster members that associate physically with the Abell clusters (Robertson & Roach, 1990; Brown & Burns, 1991; Unewisse & Hunstead, 1991), we restrict the redshifts of all the radio sources to be larger than 0.5. This reduces the number of radio sources to 224, in which we have excluded the quasars without measured redshifts and the galaxies due to their scarcity.

The second sample of radio-bright quasars is extracted from the 2-Jy all-sky survey of Wall & Peacock (1985) at 2.7 GHz. This sample covers the same area of the sky as the 1-Jy one and comprises 233 sources. With our redshift limit of  $z > 0.5$ , the subsequent sample contains 103 sources, among which 62 quasars have spectroscopically measured redshifts while the estimated redshifts have been given for the rest using the optical magnitude – redshift relation. We have included the estimated redshift quasars in order to reduce the statistical fluctuations arising from the small number of sources.

## 3. Statistical results

We search for the number excess of Abell clusters in the vicinities of background quasars. The search range is a circle of radius of  $\theta$  centered on each of the quasars of the subsamples. We count the clusters of galaxies that locate within the search radius,  $N(< \theta)$ , and compute the surface number density of Abell clusters over the search area using  $s(< \theta) = N(< \theta)/(n\pi\theta^2)$ ,  $n$  denoting the total number of quasars in the subsamples. The enhancement factor is finally  $q(\theta) = s(< \theta)/s_o$ , where  $s_o$  is the mean surface number density of Abell clusters. Note that the center positions of Abell clusters have an uncertainty of  $\sim 1$  arcminute and it then turns out that a search radius less than 1 arcminute is meaningless.

Table 1 lists one of the results, the detected Abell clusters within a radius of  $\theta \leq 0.3^\circ$  around quasars from the 224 1-Jy sample. The same method is used over different search ranges in both the 1-Jy and 2-Jy samples. The number of detected Abell clusters has been given in Table 2, and the variations of enhancement factors normalized at  $\theta = 3^\circ$  with the search radii are shown in Fig.2 and Fig.3 for the 1-Jy and 2-Jy samples, respectively. The error bar is the standard deviation in each measurement.

## 4. Discussion

Unfortunately, significant number excess of Abell clusters in the directions of background radio-bright quasars have not been detected in both the 1-Jy and the 2-Jy samples, in comparison with the recent claim (Rodrigues-Williams & Hogan, 1993) that there exist strong associations between the foreground

galaxy clusters with the background bright quasars. This might be due partially to the small numbers of source samples used in the present paper. The enhancement factor is actually equal to unity within  $1\sigma$  level in the 1-Jy sample, despite the fact that the gravitational lensing pair of Abell 2584 – QSO 2319+272 (Stickel & kühr, 1992) is among the list of Table 1. The situation is better for the 2-Jy sample, which results in an enhancement of  $q = 1.51 \sim 3.02$  above  $1\sigma$  level within  $\theta = 0.3^\circ$ . This enhancement could be the result of statistical gravitational lensing. If this is the case, one may conclude that the associations of Abell clusters with distant radio-bright quasars exist on scale of  $\sim 20$  arcminutes, the average radius of Abell clusters (Brown & Burns, 1991).

Gravitational lensing fits (see Fig.2 and Fig.3) to both sets of data have been done using singular isothermal models for matter distributions in Abell clusters. The critical radius in the fit to the result of the 2-Jy sample is  $\theta_c = 0.2^\circ$ . We can then find the velocity dispersion ( $\sigma_{||}$ ) to be required for the fitted  $\theta_c$  in terms of the definition of critical radius in a singular isothermal model:  $\theta_c = 4\pi(\sigma_{||}/c)^2(D_{ds}/D_s)$ , where  $D_{ds}$  and  $D_s$  are the angular diameter distances of the Abell clusters (lenses) and of the observer to the quasars (sources), respectively. Taking the typical redshift of Abell cluster to be 0.1 and that of distant radio-bright quasar to be 1, and using the above fit of  $\theta_c$  to the 2-Jy result (Fig.3), we estimate the velocity dispersion  $\sigma_{||} \approx 5500\text{km/s}$ . Surprisingly, the required velocity dispersion is  $\sim 5$  times larger than the actual values for Abell clusters, making the gravitational lensing hypothesis be unlike for the detected associations of Abell clusters with distant radio-bright quasars on scale of  $\sim 20$  arcminutes. In fact, the critical radius of a rich galaxy cluster alone is smaller than 1 arcminute (Wu & Hammer, 1994), in contrast to the large values of  $0.2^\circ$  in the above lensing model fit.

Nevertheless, a similar feature appeared also in the study of quasar-galaxy associations. Recall that to reach a modest enhancement factor of 2.5, a velocity dispersion much larger than that measured for normal galaxies ( $\sim 500\text{ km/s}$ ) is needed in the lensing model of galaxies (Webster, et al., 1988; Narayan, 1989). This apparent dilemma had led one to conclude that either gravitational lensing hypothesis could not produce the observed strong associations or the mass responsible for the statistical lensing is not well modelled by a population of isolated galactic masses. The similar conclusions can now be drawn for the possible associations of Abell clusters with distant radio-bright quasars seen in the 2-Jy sample. We believe that if the 2-Jy radio quasar-cluster associations above  $1\sigma$  level are real, the gravitational matter responsible for the observed effect is not well represented by an isolated cluster although a single model with large velocity dispersion can produce the  $q \sim \theta$  curves shown in Fig.3. All the matter inhomogeneities along the line of sight to the distant quasars can contribute the gravitational effect and enhance the lensing magnification. Therefore, we should consider the above estimated velocity dispersion, hence the mass, to be the total mass integrated along the light path to the distant quasars. In this case, the weak lenses of large-scale structures in the universe should be taken into account (Bartelmann & Schneider, 1993a,b,c).

Another possibility to get a high enhancement by an isolated cluster of galaxies is that the slope of the number counts of the radio-bright sources with flux is intrinsically steeper than the observed one. Note that the present estimate of  $q$  depends on the assumption that the observed number counts of radio-bright sources are unaffected by gravitational lensing. However, the  $q \sim \theta$  fit to the 2-Jy sample in Fig.3 can be equally made for a normal cluster by using a steeper slope ( $> 1.62$ ) for background radio sources. This implies that the “lensing unaffected background hypothesis” is questionable. The discovery by Rodrigues-Williams & Hogan (1993) reaches essentially the similar conclusion.

The associations of distant radio-bright quasars with foreground galaxy clusters we have detected are not as significant as the ones for distant optical-bright quasars ( $B \leq 18.5$ ) (Rodrigues-Williams & Hogan, 1993). This arises probably due to different sizes of the two kinds of radiations associated with quasars.

Quasar can be regarded as a pointlike source in optical wavelength while its radio emission stems from an extended region. For a disk source with radius of  $R_s$  the maximum magnification by an isothermal sphere as lens is  $A_{max} = 1 + 116.35(\sqrt{1+z}/(1+z))(\theta_c/10'')(R_s/10\text{kpc})^{-1} h_{50}^{-1}$  (Wu & Hammer, 1994), which prevents from reaching a relatively high magnification. The optical continuum emitting region in quasar estimated from its variability is of  $\sim 10^{-3}$  pc and therefore, very large magnification appears to be possible. Hence, optically selected distant quasars may show much stronger associations with foreground galaxy clusters than radio selected ones. This explains the difference of the significances in the two searches for distant bright quasar-cluster associations.

## 5. Conclusions

The strong associations between distant ( $z > 0.5$ ) radio-bright ( $\geq 1\text{Jy}$  at 5Ghz and  $\geq 2\text{Jy}$  at 2GHz) quasars and Abell clusters have not been seen, which have probably arisen from the scarcity of the source samples used in the present paper. Nevertheless, above  $1\sigma$  level the 2-Jy radio sample does show an association with the foreground Abell clusters on scale of  $\sim 20$  arcminutes. 9 Abell clusters have been detected within  $0.3''$  of the 103 quasars in the 2-Jy sample while only 4 are expected to see if Abell clusters distribute randomly on the sky. Gravitational lensing hypothesis can very well fit to the enhancement variations with the search range in the 2-Jy sample if (1) a considerably large mass is assumed to associate with Abell clusters, in the sense that the detected associations might be the result of weak lensing effect of clusters of galaxies tracing large-scale structures in the universe, and/or (2) the intrinsic radio-bright sources have a steeper slope with flux than the actually observed one, in the sense that the “lensing unaffected background hypothesis” is questionable.

Following the discovery of quasar-galaxy associations, including optical quasar-galaxy, radio quasar-galaxy and radio quasar-IRAS galaxy, and of optical bright quasar-cluster associations, we have extended the searches for the associations to the radio-bright quasars and the clusters of galaxies. Unfortunately, the small samples of background sources have led to some large statistical fluctuations in the present searches. A preliminary result is that there may exist the associations between the high redshift radio-bright quasars and the low redshift clusters of galaxies on scale of a typical size of the Abell cluster. If this is the case, our result confirms the recent report by Rodrigues-Williams (1993) who have found a significant association ( $4.7\sigma$  level) between the foreground Zwicky clusters and the distant quasars. We are planning to extend the current work to involve the distant 3CR galaxies and to statistically search for the possible associations of the high-redshift 3CR galaxies with clusters claimed by Hammer & Le Fèvre (1990). The study of the associations of distant objects with clusters of galaxies can provide very useful information about the matter distribution on large-scales in the universe and has a strong impact on gravitational lensing hypothesis.

## ACKNOWLEDGMENTS

We are grateful to François Hammer for reading the manuscript and for valuable comments. WXP thanks CNRS and WONG for financial support.

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## Figure Captions

*Figure 1* Enhancement  $q$  of the radio-bright sources versus gravitational magnification  $A$ .

*Figure 2* Variations of number excess of Abell clusters around distant 1-Jy radio quasars. The data have been normalized at  $3^\circ$ . The fit to a singular isothermal sphere as lensing deflector is shown using a critical radius of  $0.1^\circ$ .

*Figure 3* The same as Fig.2 but for the 2 Jy sample and a critical radius of  $0.2^\circ$ .



**Table 1** Abell clusters detected within a search range  
of  $0.3^\circ$  of the 1-Jy distant radio quasars

quasar	RA (1950)	Dec (1950)	$z$	Abell	RA (1950)	Dec (1950)	$z$	richness	separation ( $^\circ$ )
0426−380	04 26 54.74	−38 02 52.4	1.030	3259	04 27.0	−38 13	(.1425)	3	0.17
0809+48	08 09 59.42	+48 22 07.2	0.871	637	08 11.4	+48 32	(.1485)	0	0.29
0954+55	09 54 14.34	+55 37 16.6	0.901	899	09 54.9	+55 31	(.1397)	1	0.14
1055+01	10 55 55.31	+01 50 03.7	0.888	1139	10 55.5	+01 46	.0397	0	0.13
1127−14	11 27 35.68	−14 32 54.8	1.187	1285	11 27.9	−14 17	.1010	1	0.28
1148−00	11 48 10.13	−00 07 13.2	1.982	1392	11 48.0	−00 18	.1382	0	0.18
1624+41	16 24 18.21	+41 41 23.3	2.550	2196	16 25.7	+41 36	.1332	0	0.28
2052−47	20 52 50.50	−47 26 19.6	1.489	3720	20 53.2	−47 13	(.1987)	1	0.23
2131−021	21 31 35.34	−02 06 40.8	0.557	2353	21 31.8	−01 49	(.1078)	1	0.30
2211−17	22 11 42.51	−17 16 33.7	2.153	3847	22 11.8	−17 16	(.1500)	0	0.024
2319+272	23 19 31.99	+27 16 19.1	1.253	2584	23 19.6	+27 17	.1184	0	0.019

**Table 2** Number of the detected Abell clusters around distant radio-bright quasars in the 1 Jy and 2 Jy samples

range $\theta$ (degree)	N( $\leq \theta$ )		$q$ (normalized at $3^\circ$ )	
	1 Jy	2 Jy	1 Jy	2 Jy
0.2	6	4	$1.63 \pm 0.69$	
0.3	11	9	$1.33 \pm 0.42$	$2.16 \pm 1.75$
0.4	12	11	$0.82 \pm 0.24$	$1.48 \pm 0.47$
0.5	18	14	$0.78 \pm 0.19$	$1.21 \pm 0.34$
0.6	32	22	$0.97 \pm 0.18$	$1.32 \pm 0.29$
0.7	45	28	$1.00 \pm 0.15$	$1.23 \pm 0.24$
0.8	56	33	$0.95 \pm 0.13$	$1.11 \pm 0.20$
0.9	77	41	$1.03 \pm 0.12$	$1.09 \pm 0.18$
1.0	92	46	$1.00 \pm 0.11$	$0.99 \pm 0.15$
1.5	198	110	$0.96 \pm 0.07$	$1.06 \pm 0.11$
2.0	368	185	$1.00 \pm 0.05$	$1.00 \pm 0.08$